

WHAT IS A PECULIAR GALAXY ?

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ABSTRACT

Following the recent surge of interest in peculiar galaxies at high redshifts we consider the definition, or lack thereof, of morphological peculiarities on a sample of local universe galaxies. Studying the morphology of local universe galaxies is also of interest in trying to understand galaxy dynamics and quantifying the relations between morphology and environment. We use classifications given by five experts for a sample of 827 APM galaxies and find that there is little agreement between them on what qualifies as a peculiar galaxy. We attempt several objective approaches : matching galaxy images to “templates”; examining the 180° Asymmetry against Light Concentration (following Abraham *et al.* 1995); and exploring angle-dependent asymmetry measures. While none of the quantities we use results in a clean distinction between normal and peculiar galaxies, there is a rough correlation between some parameters and image peculiarity. However, the mixing between the two classes is significant. We conclude that the class of peculiar galaxies is not totally distinct from the class of normal galaxies, and that what we are seeing is really a sequence. It is therefore more useful to consider distribution functions of morphological parameters. The current and possibly other, more accurate parametrisations require better data, which is becoming available through CCD imaging.

1 INTRODUCTION

Most of the observed galaxies in the local universe appear to form a morphological sequence, known as the Hubble sequence (e.g., Sandage 1961; de Vaucouleurs *et al.* 1959). The defining criteria for various types of galaxy along the Hubble sequence are mostly qualitative rather than quantitative, and thus somewhat vague (e.g., Mihalas & Binney, 1981). Nevertheless, in a recent study (Lahav *et al.* 1995; Naim *et al.* 1995a) six experts were asked to classify the same sample of 835 galaxies from the APM Equatorial Catalogue (Raychaudhury *et al.*, in preparation) and came to a reasonable agreement with each other : The rms dispersion over all pairs of experts was 1.8 types, on a scale of 16 types ranging from -5 for Ellipticals to +10 for Irregulars. The notion of a well established morphological sequence pertains to what are loosely referred to as “normal galaxies”. In addition to these, a certain (small) fraction of local universe galaxies are regarded “peculiar” to varying extents. In an attempt to better understand spiral arms, H. Arp has collected into what became his Atlas of Peculiar Galaxies (1966) many examples of galaxies which deviated in some way from the normal Hubble sequence. The morphological diversity of these peculiar galaxies is quite impressive.

So long as the fraction of peculiar galaxies was considered very small, they could be treated as individual cases that may not fit comfortably on the Hubble Sequence. This situation is now changing with the advent of imaging at higher redshifts with the Hubble Space Telescope and large ground based telescopes. As has recently been reported (e.g., Griffiths *et al.* 1994; Driver *et al.* 1995; Abraham *et al.* 1995), the fraction of peculiar and irregular galaxies at moderate redshifts appears to be much higher than in the local universe. However, the numbers quoted rely on eyeball classification by different observers, and since the notion of peculiar galaxies is even more fuzzy than that of morphologically “normal” galaxies, any reference to the fraction of peculiar galaxies (at any redshift) may be very sensitive to the adopted definition of peculiarity. Whatever definition is adopted, it is crucial that a set of *objective* parameters be found that describe galaxy morphologies faithfully at

various redshifts. Automating the process of morphological analysis is inevitable in view of the very large numbers of galaxy images now available, and an objective parametrisation is the only way to do it.

In this paper we attempt to answer three fundamental questions :

- (i) What is a peculiar galaxy ? What definition exists and should it be adopted or modified ?
- (ii) Do peculiar galaxies constitute a separate class of galaxies, or do they form a continuum that blends into the realm of normal galaxies ?
- (iii) Which *objectively measured* parameters should one use in order to define distribution functions of galaxy morphologies at all redshifts and for all inclinations ?

We treat the first question in § 2, where we describe and compare the experts' classifications. We treat the other two questions in § 3, in which we discuss ways to quantify peculiarity and describe our results using several parametrisations. The discussion is brought in § 4.

2 PECULIARITIES FROM EYEBALL CLASSIFICATIONS

When dealing with eyeball classifications of peculiar galaxies it is important to note that the term “peculiar” refers to a different kind of morphology than the term “irregular”, although there appears to be some confusion between the two in the literature. Irregular galaxies lie at the late type end of the Hubble sequence. They are rather faint and fuzzy, and have little or no bulges. Peculiar galaxies are all those galaxies whose morphology is not similar to that of any of the Hubble types, including the irregulars. Our attempts are concentrated on telling peculiars apart from normal galaxies and we include irregulars in the latter category.

From an inspection of Arp's atlas (1966) it appears that in very broad terms there are two kinds of morphological peculiarities : What we will refer to as “mild” peculiarities are deviations from the “normal” patterns expected from a galaxy of any given Hubble type, which nevertheless allow the classification of that galaxy along the Hubble sequence. Examples include dust lanes in Ellipticals and three-armed Spirals. What we refer to as “strong” peculiarities are severe disruptions of the general appearance of a galaxy, to such an extent that normal classification is either very inconclusive or totally impossible. A galaxy with a mild peculiarity may be assigned a Hubble type with the addition of a lower case “p” (e.g., SBcp). For strong peculiarities the type is simply “Pec”. However, in most cases eyeball classifications are given without explicitly defining the criteria, and this leads to confusion between peculiars and normals as well as between different extents of peculiarity.

We seek to put the notions of mild and strong peculiarities on more solid, quantitative grounds. As a first step we examine 827 galaxies from the sample of APM galaxies which was used in the comparative study of morphological classifications (Naim *et al.* 1995a). Five of the participating experts (R. Buta, H. Corwin, G. de Vaucouleurs, J. Huchra and S. van den Bergh) gave a full morphological description in addition to the numerical T-type. Of the 827 images, 222 (27 %) were flagged with some kind of a peculiarity by at least one expert. Only 22 galaxies (3 %) were flagged as strongly peculiar by at least one expert, which indeed shows that strongly peculiar galaxies are quite rare in the local universe. However, the agreement between the experts on the issue of peculiarity is not very high : of the 222 galaxies flagged for some kind of peculiarity, 125 were flagged by only one expert, 44 by two, and only 53 by more than two experts. *In only five cases did all the experts agree that the galaxy was peculiar.* The situation is not different when one restricts oneself to galaxies flagged as strongly peculiar by at least one expert : of the total of 22 such galaxies, 8 were flagged as “Pec” by two experts and only two by three experts. There were no cases of four or five experts agreeing on a strong peculiarity. These low rates of agreement between experts mean that *there is no accepted definition for morphological peculiarities.*

3 QUANTITATIVE MEASURES OF PECULIARITIES

Eyeball classifications of peculiarities appear to yield answers that are observer-dependent, and in addition are not easily applicable to large numbers of images. As suggested in our previous work on morphological classification of normal galaxies (Lahav *et al.* 1995; Naim *et al.* 1995b), automating the process is essential. Here we focus on quantitative parameters for the description of peculiarities.

Identifying a mild peculiarity could be approached by matching an image with a set of templates, each describing a certain morphological type. Work along these lines has been done (e.g., Spiekermann 1992) for the classification of normal galaxies. However, this raises an even more difficult question, namely, what is a *normal* galaxy? In other words, what variety of galaxy templates, and in particular how many of them, can be considered as sufficient to represent all normal galaxies as distinct from peculiars ? we try to answer this question below.

On the other hand, detecting a strong peculiarity may be an easier exercise, but nevertheless requires a quantitative definition. Abraham *et al.* (1995) claim that peculiar (and irregular) galaxies are much less symmetric than normal galaxies, and suggest an asymmetry parameter (A) which is based on rotating the image by 180° and subtracting the result from the

original image. This single parameter was augmented by the central concentration of light (C) parameter, which was originally suggested by Morgan (1958) and later used successfully by Kodaira *et al.* (1986). In effect, using the light concentration as a key parameter implies the a-priori assumption that peculiarities are related to late-type, disk-dominated galaxies only. We therefore examine the A parameter alone, apply it to the APM sample and generalise it into a set of five parameters.

3.1 Identifying Peculiarities by Template Matching

As a first guess at the number of galaxy templates required in order to span the full range of normal morphologies, we selected galaxies from the APM sample according to two criteria : (i) They were given definite classifications by at least five experts (As noted in Naim *et al.* (1995a), the experts reserved the right not to classify a galaxy at all, or give a partial classification such as "S", when they were very uncertain); (ii) The rms dispersion between the experts for every selected galaxy was less than 0.5 types. We then inspected the selected images by eye, and removed from the list cases of morphologies that were nearly identical to other members in the list. The goal was to end up with as diverse a collection of morphologies and inclinations as possible, while keeping the overall number of templates relatively small. The resulting list contained 35 galaxies, which represent the following seven classification bins (according to their mean types, given by the experts) :

- (i) Types [-5,-3.5] : E, 3 galaxies
- (ii) Types (-3.5,0.0) : S0, 3 galaxies
- (iii) Types [0.0,2.0] : Sa, 4 galaxies
- (iv) Types [2.0,4.0] : Sb, 8 galaxies
- (v) Types [4.0,6.0] : Sc, 9 galaxies
- (vi) Types [6.0,8.0] : Sd, 3 galaxies
- (vii) Types [8.0,10.0] : Sm/Ir, 5 galaxies

Any measure of similarity between two images should be insensitive to size and inclination differences. To ensure this, we used the image reduction software developed for the APM galaxies (Naim *et al.* 1995b). As a first stage we detected foreground stars superimposed on the galaxy image and removed them. Since the images were taken from plates, most stellar images were saturated and no point-spread-function could be well fitted to them. This means that both the detection of stars and their removal were rather crude. We then sampled each image on a series of $N_e = 30$ ellipses, all sharing the ellipticity and position angle of the whole image, but each with a different semi-major axis length. The difference D_{ij} between any two images i and j was defined as :

$$(1) \quad D_{ij}^2 = \frac{1}{N_e} \sum_{k=1}^{N_e} \frac{\sum_{l=1}^{N_k} (I^i(k,l) - I^j(k,l))^2}{N_k}$$

where the outer sum is over the N_e sampled ellipses, the inner sum is over the N_k points of ellipse k , and $I(k,l)$ denotes the sampled intensity at point l of ellipse k .

Classification of a given galaxy image was then carried out by calculating the difference between that galaxy and every template galaxy. The difference was also calculated with the template galaxy reflected about its minor axis, in order to be reflection-independent, and smaller of the two numbers was taken as the difference between the two images. Typically, our current image will resemble one template of a given type more than other templates of the same type. For this reason the difference between our image and the entire type is taken as the smallest of its differences from all the templates belonging to that type. In this way we express the classification of any galaxy in the sample by a 7-dimensional vector of these minimal distances. For normal galaxies the smallest component of this vector ought to be the one corresponding to the correct classification bin, and peculiar galaxies are expected to have large distances from all bins. We define as strongly peculiar galaxies having at least one expert assign them a "Pec" type, while mildly peculiar galaxies are defined to have no "Pec" assignment and at least three "p" assignments by the experts. With these definitions we have 34 mild peculiars and 22 strong peculiars in the sample.

Figure 1 depicts histograms of the minimal component of the distances vector for the three populations of galaxies. Naively, one would expect the minimal difference to be large for peculiars (not really close to any of the classes), while normal galaxies should be much closer to one bin, so the minimal value should be much smaller. However, as can be clearly seen from the figure, the peculiars largely follow the trend set by the normals, although some of the strong peculiars do exhibit the expected behaviour. The medians of each plot are indicated by a vertical dashed line, and do not change much from one plot to the other : The median of the normal galaxies is 0.078, rising slightly to 0.083 for mild peculiars and up to 0.9 for strong peculiars. It appears that our collection of 35 templates does not truly represent the morphological variety of the whole sample. We tried to solve this problem by increasing the number of templates we use. We repeated the above exercise for a collection of 262 templates, which were selected by relaxing the largest allowable rms of the experts' classifications from 0.5 to 0.8 types, but still requiring five definite classifications. The templates were divided among the seven classification bins as follows :

- (i) Types [-5,-3.5] : E, 11 galaxies
- (ii) Types (-3.5,0.0) : S0, 19 galaxies
- (iii) Types [0.0,2.0] : Sa, 29 galaxies
- (iv) Types [2.0,4.0] : Sb, 98 galaxies
- (v) Types [4.0,6.0] : Sc, 81 galaxies
- (vi) Types [6.0,8.0] : Sd, 11 galaxies
- (vii) Types [8.0,10.0] : Sm/Ir, 13 galaxies

Figure 2 shows the results in this case. It appears that the use of more templates has made only a small difference : The medians are now at 0.044 for normals, 0.068 for mild peculiars and 0.083 for strong peculiars. While the differences between the medians are larger than before, the mixture between the populations is still large. It seems therefore that template matching does not work properly for the distinction between normal and peculiar galaxies, although it is difficult to decouple it from the uncertainties in the experts' classifications.

3.2 Suggested Measures of Peculiarity

In an attempt to decouple the effect of vague classifications from that of inadequate parametrisation, we now turn to look for specific features which distinguish normal galaxies from peculiars. We examine two sets of parameters here : One was suggested by Abraham *et al.* (1994, 1995) and comprises the light concentration index and the asymmetry parameter (the C-A pair). We adopt the definitions they give for both parameters. The other set is a generalisation of their asymmetry parameter : We use the $N_e = 30$ sampled ellipses and define 32 radial rays, of constant angular separations ($\pi/16$). Instead of looking at differences due to 180° rotations only, we then examine five different angular separations : $\theta = 180^\circ, 90^\circ, 45^\circ, 22.5^\circ, 11.25^\circ$. Figure 3 shows schematically all the rays, a selected pair of which (at separation of 11.25° are highlighted. For any two such radial rays, k and l , we define the difference $d(k, l)$ as :

$$(2) \quad d^2(k, l) = \frac{1}{N_e} \sum_{m=1}^{N_e} [I(k, m) - I(l, m)]^2$$

where $I(k, m)$ is the sampled point at the intersection of radial ray k and ellipse m . The asymmetry at angular separation θ is then given by :

$$(3) \quad d_\theta^2 = \frac{1}{N_\theta} \sum_{(k,l) \in \theta} d^2(k, l)$$

where the summation is over all N_θ pairs of rays (k, l) such that their angular separation is θ . It is important to note that the A parameter is calculated on the entire image, while the generalised parameters are measured on rays selected from the sampled ellipses.

3.3 Applying the Parameters to APM Images

Figure 4 depicts the positions on the C-A plane occupied by normal, mildly peculiar and strongly peculiar galaxies (defined as above). The dashed lines in each plot mark the median values of each of the two parameters. The picture is essentially the same as before : there is a high degree of mixing between normals and peculiars, and telling the two kinds of peculiars apart is virtually impossible.

In figures 5-7 we show the results of applying the generalised asymmetry parameters. Figure 5 shows histograms depicting asymmetry values for each of the five angular separations, for normal galaxies. Figure 6 shows the corresponding histograms for mild peculiars, while strong peculiars are depicted in figure 7. The distribution of normal galaxies is concentrated around low values in all angular separations, as one would expect. The peculiars, in particular the strong peculiars, show an almost bimodal distribution, with the majority of galaxies overlapping on the positions held by normal galaxies and a smaller fraction lying at higher degrees of difference. The medians of these histograms are again shown as dashed vertical lines, and figure 8 shows the medians as a functions of angle of separations for all three populations. The gap between the medians is largest at angular separation of 45° , decreasing towards both ends.

It is very interesting to note that all five differences correlate with each other : Principal components analysis of these data shows that 91% of the variance are spanned by the first PC. Galaxies appear to exhibit roughly the same degree of asymmetry at all angular separations. However, these are tentative conclusions drawn from survey plate material. It may well be that repeating this exercise with CCD images will give a different conclusion. In figure 9 we show scatter plots of the five differences against the A parameter. The correlations are significant but the scatter is large. The 180° difference appears to have a shallower slope than the others with a hint of curvature, and its scatter is lower than that of the others. The scatter increases as one goes to lower angular separations. The five generalised asymmetries therefore convey more information than just the A parameter. Again, using CCD images these parameters may indicate more diversity.

Figures 10 and 11 show the strong and mild peculiars in our sample. Figure 12 shows a set of normal galaxies from the sample, for which a high 45° difference (> 0.2) was derived. Some of the objects in figure 12 look similar to some peculiars in the sample, while others appear normal but are contaminated by foreground stars. As mentioned above, the removal of stars was crude and may have been insufficient in some cases (especially for edge-on galaxy images).

4 DISCUSSION

The nature of peculiar galaxies depends on their definition. In the absence of a definition we look to expert classifiers for agreed examples. However, even the experts do not agree very well on this issue. The conclusion is that the so-called class of peculiar galaxies is in fact a mixed bag of deviations from what are regarded as normal morphologies. In some cases peculiarity manifests itself through asymmetry, but in other cases it is much more subtle and difficult to detect. The transition between normal and peculiar galaxies appears to be very smooth. One can imagine the locus of normal galaxies in the centre of morphology space, with various deviations stretching in different directions. The further away from the centre one goes in a certain direction the more peculiar the corresponding morphology. Since deviations from "normality" form a continuum, it is down to the observer who classifies the galaxy to draw the line beyond which a galaxy is called peculiar. The answer to the question "what is a peculiar galaxy" is therefore not only a matter of defining what deviations from normality to look for, but also of setting the extent of the deviation. Alternatively, and more sensibly, one can do away with classifications and simply look at distributions of galaxies in morphology space.

The variety of galaxy morphologies is so great that qualifying peculiarity through template matching can not succeed, unless one is willing to employ a vast collection of templates that incorporates each and every "normal" morphology. This is not practical, both technically (requiring too many eyeball classifications) and conceptually (there is no clear quantitative definition of normal galaxies, either). The alternatives tried by Abraham *et al* (1995) and by ourselves manage to capture only one kind of deviation from normality : a general distortion of the shape of the galaxy. Even then, "noisy" normal galaxies are mixed with truly distorted peculiars. Noise sources include contamination by foreground stars which were not fully removed. The inclination of a galaxy image also plays a role in determining how accurately parameters are measured. The problem of star removal could be dealt with on CCD images, where one can calculate a stellar point-spread function and subtract it. The quality of data is therefore of great importance, and the increasing numbers of CCD-based surveys will help in avoiding problems such as insufficient dynamic range and non-linear response, which are typical of plate material. It is certainly worth while revisiting the analysis of this paper with CCD images of galaxies.

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Figure Captions :

Figure 1 : Minimal Difference vs. Classification Bin, using 35 templates, for three kinds of galaxies. Top Left : Normals; Top Right : Mildly Peculiar; Bottom Right : Strongly Peculiar.

Figure 2 : Minimal Difference vs. Classification Bin, using 262 templates, for three kinds of galaxies. Top Left : Normals; Top Right : Mildly Peculiar; Bottom Right : Strongly Peculiar.

Figure 3 : Schematic Description of the Radial Rays used in Calculating the Generalised Asymmetry Parameters.

Figure 4 : Distribution of Normal and Peculiar Galaxies on the C-A Plane. The medians of each parameter are also indicated.

Figure 5 : Distribution of the Generalised Asymmetry Parameters for Normal Galaxies.

Figure 6 : Distribution of the Generalised Asymmetry Parameters for Mildly Peculiar Galaxies.

Figure 7 : Distribution of the Generalised Asymmetry Parameters for Strongly Peculiar Galaxies.

Figure 8 : Medians of Generalised Asymmetry for Normal and Peculiar Galaxies.

Figure 9 : Generalised Asymmetry Parameters vs. the A Parameter.

Figure 10 : The Strong Peculiars in our sample.

Figure 11 : The Mild Peculiars in our sample.

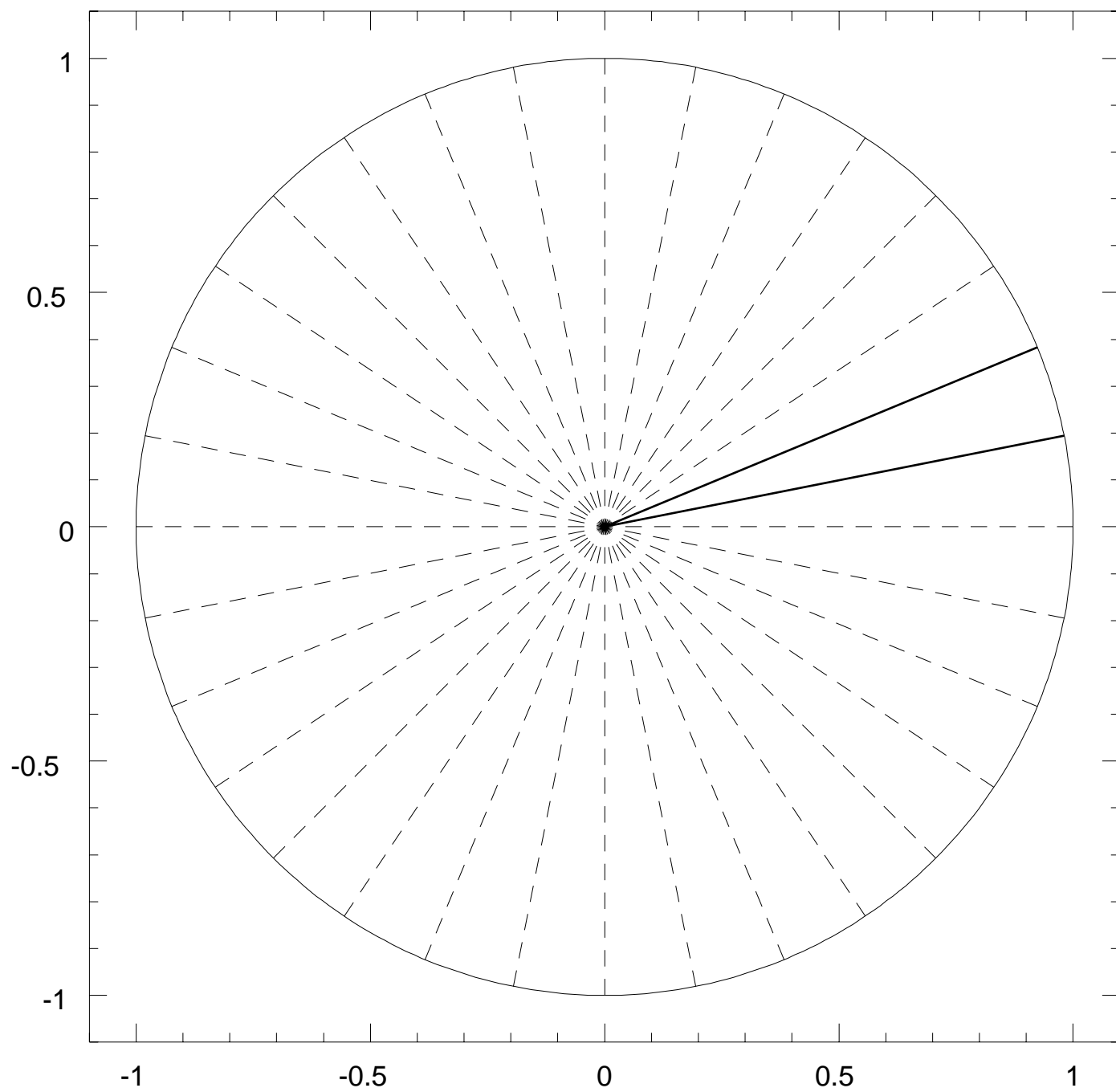
Figure 12 : Asymmetric Normal Galaxies in the Sample.

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